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Chapter 5

The superconducting solenoid

5.1 Introduction

Momentum analysis in GlueX will be provided by a 2.2 Tesla superconducting solenoid magnet. This solenoid was built at SLAC ca. 1970 for the LASS spectrometer and subsequently moved to LAMPF in 1985 for inclusion in the MEGA spectrometer. The MEGA Experiment and the solenoid were decommissioned in place in 1995. The MEGA experiment was dismantled and recycled in the spring and summer of 2002. The solenoid was shipped from LANL to the Indiana University Cyclotron Facility (IUCF) for coil refurbishment and testing in October 2002. Currently all four coils have been extensively tested and coils one and two have been completely refurbished. Refurbishment efforts on coils three and four will start in the fall of 2004. The solenoid magnet was designed and built using standards that today would be considered ultra-conservative. The magnet employs a cryostatically stable design and uses cryostats that were designed to be easily opened for service with hand tools. The inspection of the magnet performed at LANL in 2000 concluded that the solenoid was still in excellent condition and worthy of the use, time and cost involved in relocation and refurbishment. Nevertheless, the magnet support systems are now 30 years out of date so even though the magnet was in good condition considering its age, it still required some repairs, maintenance, updating, and modifications for use as part of the GlueX experiment.

5.2 Brief Description

The magnet is described in a technical note [?] and some relevant portions of that description are quoted below. Table 5.1 summarizes important magnet parameters. The refrigeration units are not currently available, and alternatives will need to be found.

Inside winding diameter of SC coils	80 *inches*
Clear bore diameter	73 *inches*
Overall length (iron)	183 *inches*
Inside iron diameter	116 *inches*
Outside iron diameter	148 *inches*
Coil-to-coil separation	11 *inches*
Total iron weight	200 *tons*
Central field	22 kG
Conductor current	1800 A
Total stored energy	36 MJ
Inductance	22 H
Total helium volume (including reservoir)	5,000 *liters*
Operating heat load (liquid He)	30 *liters/hour*
Operating heat load (liquid nitrogen)	30 *liters/hour*
Cool-down time	2 *weeks*
Copper to superconductor ratio	20:1 (grade A) 28:1 (grade B)
Total conductor length	117,600 *feet*
Total conductor weight	29,000 *lbs*
Turn on time	20 *minutes*
Turn off time (normal)	20 *minutes*
Axial load per coil due to magnetic forces	280 *tons*

Table 5.1: Summary of characteristics of the solenoid as used in the LASS configuration.

The LASS solenoid magnet provides a 22 kG magnetic field parallel to the beam direction. The clear bore inside diameter of the magnet is 73 *inches* and its final as modified overall length is 195 *inches*. Within the clear bore region the field homogeneity is $\pm$ 3%. Along the beam axis the field homogeneity improves to $\pm$ 1 %. The solenoid is constructed of four separate superconducting solenoidal coil-cryostat units [?] and A segmented 215 *ton* iron flux return path that surrounds and supports the coil assemblies. A common liquid helium reservoir is located atop the solenoid providing the gravity feed of the liquid to the coils.

The superconductor used is a stabilized, composite, twisted, multi–filament niobium–titanium wire. The wire is made by soldering the superconductor composite between two copper strips to form a rectangular cross section 0.763 x 0.533 cm^2. The coil is wound directly on the liquid helium vessel inner cylinder wall. As the coil is wound, a 0.20 *inch* thick stainless steel support band and a mylar insulating strip are wound along with it for mechanical support and insulation. Cooling by the liquid helium is accomplished from the edges. Each of the four solenoidal windings has its own predetermined number of turns, the configuration being selected for optimum central field homogeneity consistent with the requirement of the inter-coil gaps and the large downstream end opening.

The liquid helium vessel is surrounded by a liquid nitrogen cooled radiation shield and this assembly is centered in the vacuum tank by a circumferential series of tie bolts designed for minimum conductive heat flux to the helium bath. Radial centering and support are achieved by four low conductance hangers arranged in a spiral pattern. Various tie rods and hangers are instrumented with stress bolts to measure the tremendous forces on the assembly caused by the magnetic fields.

The inductance of the coil is 22 *Henries* , and the magnet is run at 1800 *Amperes*. The liquid helium volume is $\approx$ 5000 *liters* and the heat load is $\approx$ 50 *watts*. Refrigeration at Hall D will be supplied by a small local refrigerator of 200 watt capacity. This conservative nature of the design of the magnet, cryostat and the superconductor itself, has produced a stable, reliable and safe superconducting magnet.

5.3 Evaluation of solenoid after MEGA

The LASS/MEGA solenoid was inspected in April 2000 by a team from the GlueX collaboration, JLab staff and two of the original designers of the magnet. This team met at Los Alamos with the MEGA staff and inspected the MEGA magnet installation and the fourth coil. Except for two small mechanical vacuum pumps the system was completely intact. The fourth coil was found sealed in its original shipping crate. The fourth coil iron yoke ring, yoke stand and coil insertion tool were all found in storage. Several transportainers were found filled with magnet documentation including original drawings and micro film copies, log books, operating data, magnetic data, photo albums documenting all phases of the magnets life, manuals, calculations, and spare parts.

The committee concluded that "the condition of the magnet is excellent and if cooled down in place would in all likelihood work!" Subsequently Jefferson Lab formally transferred the solenoid system from Los Alamos to JLab as of October 2001, except for two items that are to be retained by Los Alamos, neither of which are required at JLab. A Memorandum-of-Understanding (MOU) was negotiated with LANL to cover all aspects of the MEGA experiment dismantling. This work, performed by a JLab crew, was begun in November 2001 and was completed in February 2002. All work was governed by a detailed Hazard Control Plan written to meet LANL safety standards. The solenoid was dismantled by a heavy rigging contract crew and shipped to IUCF. A detailed MOU was negotiated between JLab and IUCF to receive the solenoid, perform all the upgrade and maintenance work on the four coils, and perform limited cryogenic tests with LN2 of the four solenoid coils.

5.4 Dismantling and relocation

Our initial inspection showed that the MEGA setup was substantially unchanged since completion of the experiment years ago. The magnet still contained all the physics equipment for the MEGA experiment and was still connected to various utilities and piped services. The magnet was still connected to its power source. Further, there were small quantities of activated materials and hazardous materials within the MEGA installation. Each of these conditions had to be addressed by a comprehensive Hazard Control Plan (HCP) for the deactivation and disassembly of the MEGA experiment installation, and many items and materials may only be handled by certified personnel. The use of Los Alamos cranes and lift vehicles is similarly restricted.

JLab staff, including personnel from the JLab Radiation Control Group, were appropriately trained to perform all non-trade work. Small items were dismantled by JLab staff following the thorough deactivation of energized systems by LANL certified staff. The removal of hazardous and activated materials was performed by JLab staff under LANL supervision, and all removed materials were certified radiologically by JLab staff for free release. A large quantity 175 cubic yards of materials were removed from the MEGA installation, sorted and recycled by JLab staff. The entire process was completed in February 2002, ahead of schedule and under cost.

The actual solenoid dismantling, removal and shipping was performed by a private rigging contractor under contract from JLab with some on site LANL coordination and JLab supervision.The rigging and shipping contract was awarded by JLab to Lockwood Brothers of Newport News Virginia. The work of dismantling, loading and shipment to Indiana was completed in October 2002. The Shipment to IUCF consisted of 14 truck loads by common carrier. Unloading at IUCF into storage was performed using IUCF's crane and contract rigging staff and a large rented crane for the yoke segments.

5.5 Summary of proposed modifications

IUCF was chosen to perform the solenoid coil modifications due to availability of a skilled technical work force and facilities at an attractive cost on a favorable timescale. After the four coils are completely refurbished at IUCF the solenoid will be returned to JLAB for addition of new support systems including the DC system, control system and cryogenic interface. Testing of individual coils at 4.5 Kelvin and a full solenoid recommissioning test are planned prior to installation in Hall D.

There are numerous modernization, compatibility and maintenance tasks that must be performed to insure continued reliability of the solenoid. Most of the tasks listed below are straightforward, and involve changes needed for basic compatibility with existing JLab systems and codes, or to replace items that are obsolete and no longer serviceable. However, substantial design effort is still required for many of the solenoid improvements, and further analysis is needed to calculate and understand the solenoid magnetic performance. A description of the magnetic simulation effort can be found in Section 5.6.

1. Experiment related modifications
    - Inclusion of "fourth coil"
    - Closing of yoke gaps
    - Thickening of fourth gap iron insert
    - Thickening of downstream "pole cap"
    - symmetric opening in upstream pole cap to match downstream
    - Stands to increase the solenoid centerline height to 3.5 meters
2. JLab compatibility
    - Cryogenic interface
        - New JLab standard u-tube bayonet sockets

    - New JLab standard JT type valves and actuators
    - Cool down heat exchanger and controls
    - Relocated Helium reservoir
    - Burnout proof current leads
    - Replacement of LN2 reservoir
    - Replacement of LN2 and LHe level sensors
    - JLab standard U-Tubes
    - Transfer line to JLab CHL (not strictly part of magnet)
  - Controls interface
    - Modern PLC and software
    - EPICS compatible controls and interface
  - DC systems
    - NEC compatible energy dump and dump switch
    - New DC Power supply to match GlueX required performance
    - DC bus compatible with power supply relocation

3. Serviceability items
   - Controls and instrumentation
     - Data Logger
       * Upgrade to instrumentation and signal processing electronics
       * Remote control power supply link
       * Replacement for interlock PLC retained by LANL
       * Upgrade to quench voltage and current lead voltage detection
       * Magnetic field monitoring probe(s) and readout
       * Data cables as needed to allow relocation of controls
   - Vacuum systems
     - Replacement of oil diffusion pump system with a modern turbo pump system.
     - Replacement of vacuum instrumentation as needed.
4. Maintenance items
   - Replacement of cryostat vacuum system o-rings

- Replacement of LN2 shields to eliminate 30 year old leaks
- Leak testing and repair of Helium space leaks as needed if found
- Maintenance or replacement of thermal insulation systems as needed
- Test and maintenance of High Voltage insulation systems as needed
- Maintenance of vacuum valves and gauges
- Maintenance or replacement of internal instrumentation and wiring
- Replacement of internal strain gauges known to be faulty
- Replacement of 30 year old existing electronics and signal conditioners
- Replacement of existing data and instrumentation cabling
- Replacement of existing instrumentation vacuum feed-throughs

5.6 Magnetic Modifications Needed

The original SLAC configuration of the solenoid allowed for gaps in the return yoke so that wire chambers could be inserted from the outside. Further, in the LASS and MEGA installations the Cerenkov detector had to be located at large radius due to the presence of high magnetic fields near the downstream end of the solenoid. The source of these high fields has been investigated using a 3D TOSCA model of the yoke and coil and various methods to reduce these "stray" fields have been explored.

The solenoid was designed with a segmented yoke and four cryostats with sub-coils inside. There are a total of seventeen sub-coils located within the four cryostats, with the current density distributed by varying the number of turns. This was done to produce a more uniform internal field and to compensate for the gaps in the yoke and most prominently, for the asymmetric enlarged opening in the downstream pole cap. The seventeenth coil is very large, approximately four times the size of its neighbors. The other 16 coils vary by some few percent from each other. The seventeenth coil is needed to compensate for the large "Z" gradient in the field which is a consequence of the large opening in the yoke.

The coils further had to be operated at higher currents to drive the extra gap caused by the spaces in the yoke. The downstream pole cap was highly saturated due to the proximity of the thirteenth coil to the pole cap and the higher currents.

The following yoke modifications will reduce the saturation in the pole cap and lower the stray field in the region where the GlueX Cerenkov will be located:

1. Replace the air gaps with iron rings. This lowers the required operating current to achieve the same central field. The lowering of the local fields especially around coil seventeen helps reduce pole cap saturation.

2. Increase the distance in "Z" between the seventeenth coil and the downstream pole cap. This lowers the local field near the pole cap and thus lowers the saturation.

3. Increase the thickness of the pole cap by adding an iron disk to dilute the pole cap field and reduce saturation.

These yoke modifications will reduce the stray field levels in the Cerenkov region from ∼700 gauss down to ∼50 gauss, low enough to be shielded by thin iron and Mu-metal shields.

5.7 TOSCA simulations

5.7.1 Introduction

The original solenoid magnet was designed without the benefit of modern 3D magnetic modeling, yet the magnet has worked long and well in two experiments. But there has been a persistent difficulty with downstream stray fields, as noted above. Thus we have created a 3D TOSCA model of the solenoids fields to study the problem in detail and design a remedy.

5.7.2 TOSCA Model

The yoke and coils have been modeled using the TOSCA 3D magnetic analysis software. This model was prepared with geometry that allowed simulating the effect of closing the yoke gaps or creating new gaps, or opening or closing the ends by simply changing materials definitions.

The solenoid current distribution consisting of 17 separate windings distributed among the four coil-cryostats was modeled exactly.This permitted confirmation of the 1970 vintage field trimming that was performed with a SLAC computer code know as "Nutcracker". This 2D code proved to have done an adequate job of distributing the current to achieve the desired 1 %

homogeneity along the axis. The Nutcracker code failed to predict the substantial nonlinear effects of yoke saturation effects especially at the down stream end of the solenoid and the full effect of the four gaps. This saturation and the four yoke gaps were together responsible for the large stray fields that were a part of the original design and influenced aspects of experiment design especially PMT placement and shielding.

The solenoid magnetic field as currently modeled is based on the actual distribution of current within the four coil cryostats and the actual details of the yoke construction. The yoke modifications for the benefit of the GlueX experiment have also been included. The current distribution of the solenoid can not be modified and therefore the details must be included to accurately model the magnetic fields for experiment simulation taken and to test the effect of various modifications. The TOSCA model also provides valuable design information about the magnetic environment as seen by each detector system. The modifications to the yoke are a mix of requirements from GlueX physics, the need to lower external fields, and modifications to provide better access for the GlueX detectors. The TOSCA model is designed to evaluate the yoke modifications needed to lower the external fields. The TOSCA modeled internal fields have already been valuable as the source of magnetic fields for the Geant simulations.Further magnetic simulation work will be performed to study more carefully the effect of all the above changes on the exact B vs I excitation curve, the inductance and stored energy and the forces on the coils. Generally filling in the yoke gaps will lower all of these quantities but the exact values remain to be confirmed.

The volume modeled is a 45 degree slice of cylindrical geometry that contains a yoke segment and the surrounding air. The space modeled extends from -500 inches to + 600 inches along the z axis and out to a radius of 500 inches with the solenoid origin near zero in Z. This modeled space is subdivided into regions that contain air or iron, or reduced potential regions that contain currents. The volume modeled has 334,000 linear elements. With the high subdivision already present, we obtain adequate accuracy without the extra computational time required using quadratic elements. A full nonlinear computation is used in the iron based on the properties of generic alloy 1010 magnet steel, which is similar to the actual steel of the solenoid yoke. The actual 17 coils are modeled as full 3D current distributions superimposed on the 45 degree iron and air geometry. TOSCA uses symmetry to compute the fields in all space. The 45 degree segment of yoke is subdivided according to actual SLAC dimensions and all iron features and details are modeled. Additional geometry has been included to simulate the extra gap on the upstream end that has been suggested for allowing cables to exit the yoke.

Also, by simply changing the iron to air on the upstream pole cap one can calculate the effect of a symmetric magnet, i.e. one with both ends open. The effect of extending the yoke geometry by adding extra iron to the downstream end was studied by simply extending the existing geometry.

5.8 Preliminary results

Four GlueX models were investigated. The original and last configurations are shown in Figure5.1. All four models use identical coil models and identical current densities. The integral field increases by 2.6 % as a result of filling the gaps. The other modifications have no significant effect on the total field. This effect can be easily understood since most of the flux must return through the original gaps. Thus filling them with iron must have a large effect on the field integral while only some of the flux is effected by the other changes, and thus a minimal effect on field integral is seen.

Model Number	Max Field (G)	Min Field (G)	Low-Field Area (%)	$\int B \cdot dl$ (T·Inches)
Hall D 107	1067	523.0	none	302.8
Hall D 106	351	82.5	none	311.0
Hall D 103	241	56.7	17	311.3
Hall D 105	158	45.7	50	310.8

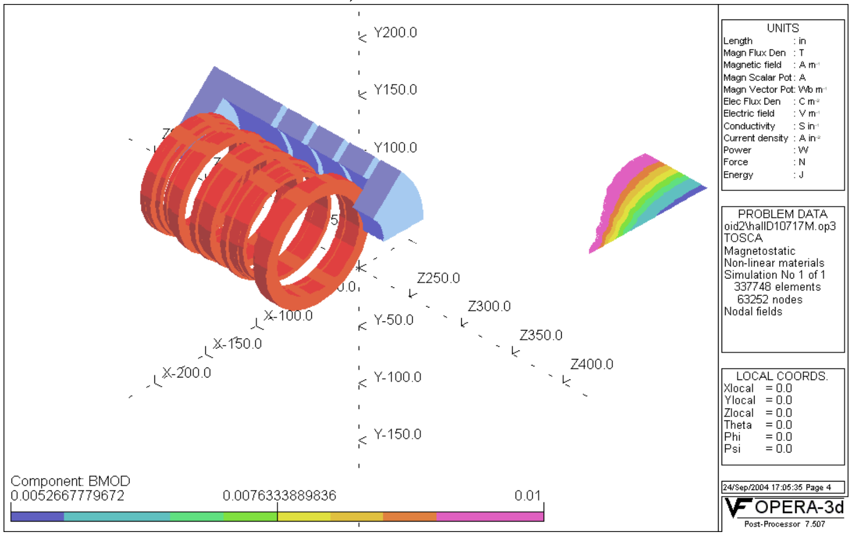
Table 5.2: Field parameters for the region between 50 and 80 in radially, where Cerenkov photomultiplier tubes might be placed. The entries correspond to the maximum and minimum B fields, and fractional area with field below 75 Gauss. Also given is the on-axis field integral for each TOSCA model.

We briefly describe each configuration:

Hall D 107 has the iron yoke and coil configuration of the original LASS solenoid as it was used at SLAC. This model is to provide a baseline for comparison and to compare with historical calculations and measurements. The model has the original segmented yoke with the four original 6 inch air gaps. *This model should be used to measure the effectiveness of the yoke changes which are the subject of the other three models.*

Hall D 106 has the SLAC yoke but with the four 6 inch gaps filled with the same iron as the rest of the yoke. This was a requested change and it

a) Hall D 107



b) Hall D 105

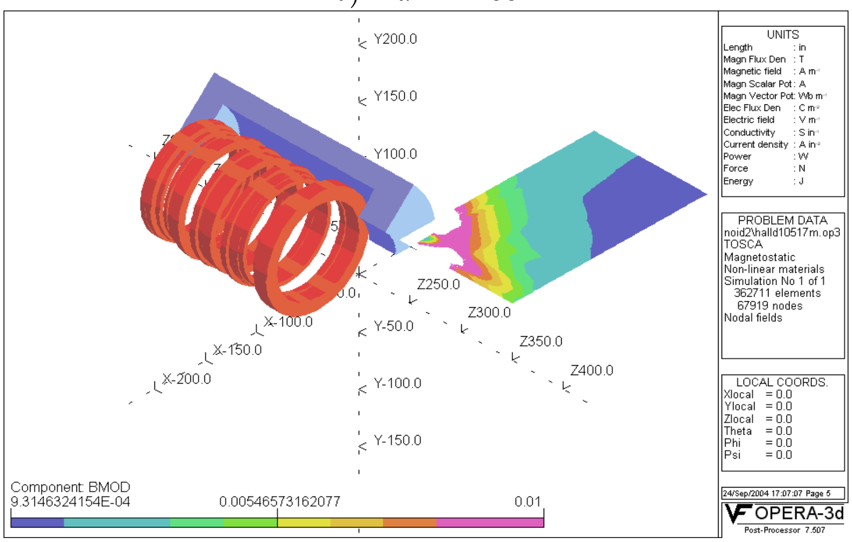


Figure 5.1: TOSCA models for a) the original magnet configuration and b) configuration that fills the gaps with iron, extends the fourth gap and thickens the pole. Both figures show the model for the coils (solenoid and 13th coil ring) and a 45 degree pie slice of the yoke iron. Also shown is a contour plot of fields which are less than 100 G in the region of 50 to 240 in radially and 190 to 300 in along the axis. This is a region that could be considered acceptable for placing photomultiplier tubes. Note that in the bottom configuration the region of low field begins at the iron, allowing detectors to be mounted near the solenoid. The magnetic field scale is in Tesla.

has the effect of lowering the external fields. You can clearly see that the external fields are in general lower, especially in the regions where it would be desirable to locate photo tubes.

Hall D 103 has the four gaps filled with steel and gap four extended from 6 inches to 12 inches. This modification was selected because of the extreme saturation in the yoke that was observed around the 13th coil. Fields as high a 3 Tesla are observed near the 13th coil. Moving the yoke further away from the 13th coil will lower the yoke saturation and thus make the yoke more effective in collecting external flux and channeling it back within the yoke iron.

Hall D 105 has the down stream "pole cap" thickened from 20 inches to 26 inches. This is in addition to filling the gaps and extending the fourth gap. This modification was selected to further reduce saturation levels in the yoke and thus reduce further the external fields.

We studied the external fields in the region where Cerenkov photomultiplier tubes may be located. The region extends in z for 20 inches and in R from 50 to 80 inches. This 20 inch by 30 inch space is kept a constant 10 inches from the down stream yoke end for the four models discussed above. Models Hall D 107 and Hall D 106 have the patch of space located at from 199 to 219 inches in Z. Model Hall D 103 has the patch located at 205 to 225 in Z because the yoke has been lengthened by 6 inches overall. Model Hall D 105 has the patch located at 211 to 231 in Z due to the extended gap and the extra pole cap thickness adding 12 inches overall to the yoke length. Thus the four patches are a constant distance from the yoke end and clearly show the substantial improvements that are possible. The model Hall D 105 has a substantial volume ($\sim$ 50 %) with fields between 46 and 74 gauss (see Table 5.2). These fields can be shielded by a combination of soft iron and Mu-Metal tubes. As this region extends from 65 to 80 inches in radius, the photomultiplier tubes for the Cerenkov could be located much close to the detection volume. A maximum distance of about 2 meters ($\sim$80 inches) is certainly possible. Figure 5.2 plots the computed fields for the four models as a function of radial distance in the area where we expect to place sensitive detectors, and Table 5.2 summarizes the characteristics for each case. Clearly there are large regions close to the detection volume where tubes could be located. It is also obvious that simply moving further out can have the same effect. Indeed the original solution chosen at SLAC was to locate the tubes at 4 meters where the fields are $\sim$75 gauss for the original SLAC /LASS geometry.

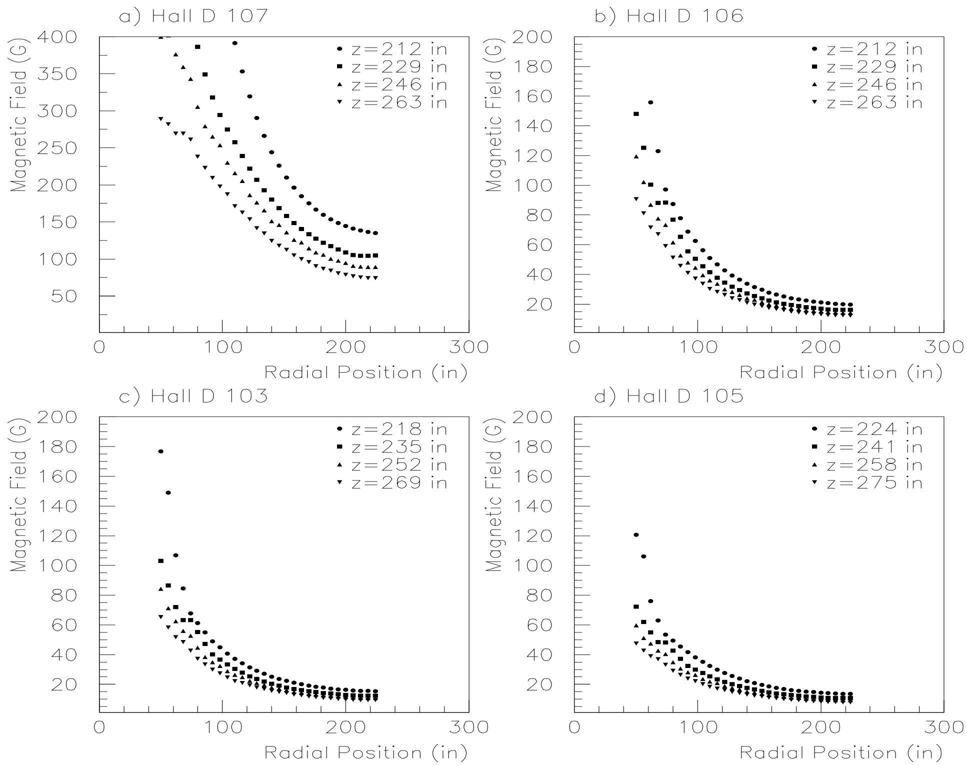


Figure 5.2: Magnetic field as a function of radial distance at constant distance along the z axis for the four different configurations of the solenoid. Note the scale change for plot a).

The modifications computed above can achieve these field levels in a much more efficient manner.

5.9 Compensation for the removal of the upstream plug

The collaboration desires a matching full aperture hole (73 inch diameter) in the upstream yoke to provide access to the detector volume for service, installation and support, and also to provide a route for cables to exit the upstream end of the magnetic volume. This upstream hole has the same effect on the internal field quality as the downstream hole and thus must be studied carefully. The downstream hole in the yoke is the same diameter as the cryostat inner diameter, 73 inches. This opening is equivalent in magnetic effect to boring a large hole in the center of the pole of a dipole magnet because the end yoke pieces for the solenoid are in fact the poles. The designers of the solenoid compensated for this large hole by increasing the current density in coil # 4, which has four times the average number of Amp-turns of the other 16 coils. This compensates for the missing iron and also contributes to the nearby yoke saturation and stray fields that we dealt with in the previous sections.

We examined four options to deal with the loss of field integral and flatness caused by the new opening: a) no action, b) creating a gap in the upstream yoke, c) increasing the current by 15% in all the coils of cryostat # 1, and d) filling the hole with the proposed upstream iron-scintillator calorimeter veto and making gaps elsewhere in the yoke to provide cable access. Figures 5.3a and 5.3b show the on-axis magnitude of the field through the solenoid for the various options discussed above. Fig. 5.3a is the nominal configuration with the upstream plug in place and Fig. 5.3b is with the new upstream hole. All other modifications mentioned earlier are included. The loss of field integral in the backward direction is not a significant problem, but the reduction of flatness has the effect of increasing the computation requirements for analysis. Clearly, an improvement in the upstream field flatness is desirable. We detail the three options considered:

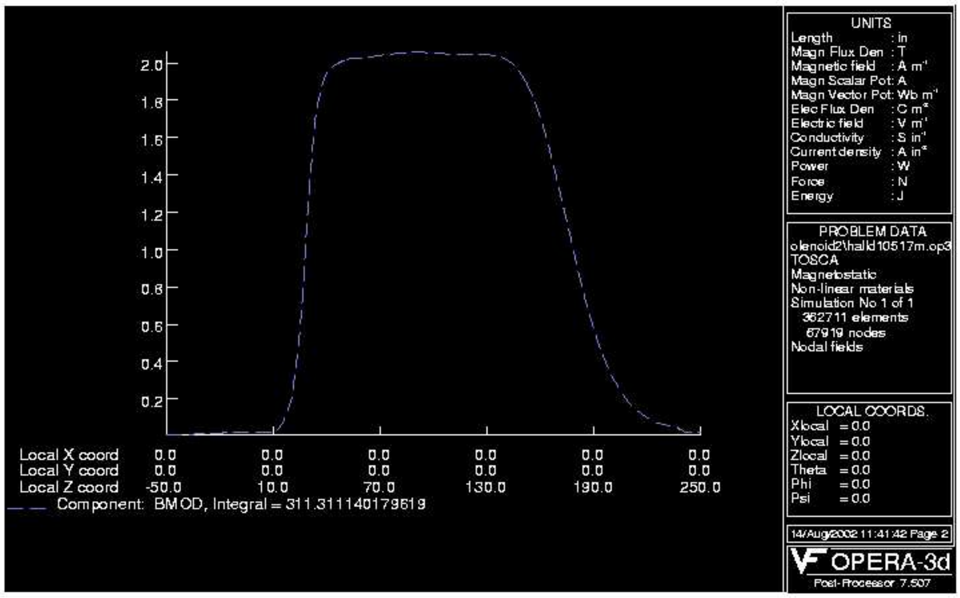
New upstream yoke gap

> Creating a new upstream yoke gap was examined in the first round of magnetic simulations and the conclusion was that this creates more of a problem than it solves. The new gaps make a lot of exterior field that can get into phototubes and it adds the complication to the assembly that cables, the yoke and detectors are now linked. The new gaps do not cause a loss of good field region but it does reduce the integral on axis.

Increase current in cryostat # 1

> Increasing the current in the 7 coils inside cryostat # 1 by approximately 15% has the effect of increasing the local Amp-turns to boost the field back up and replace the flux lost by enlarging the upstream yoke hole. This can easily be accomplished by stacking a floating DC power supply across cryostat # 1 to enhance the current relative to the main current. The main current power supply provides 1800 A to all 4 cryostats in series. In this way all 17 internal coils are in series and have the same

a)



b)

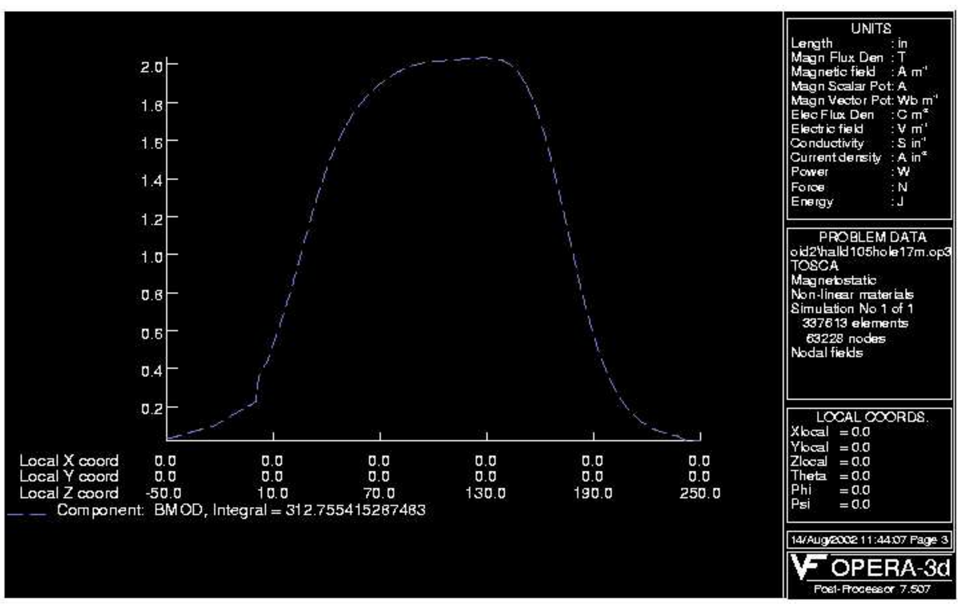
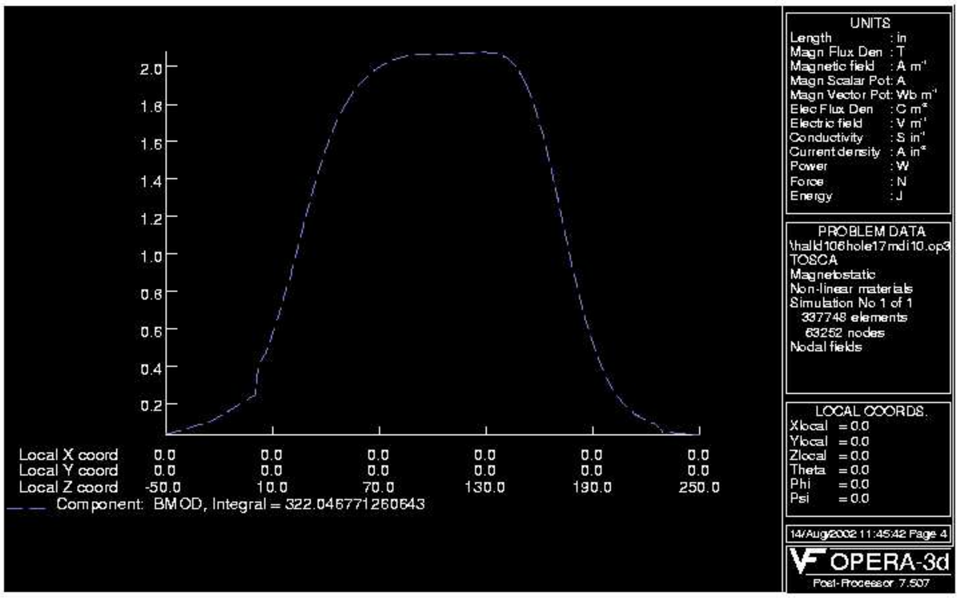


Figure 5.3: a) Standard configuration. b) Standard configuration without upstream plug.

c)



d)

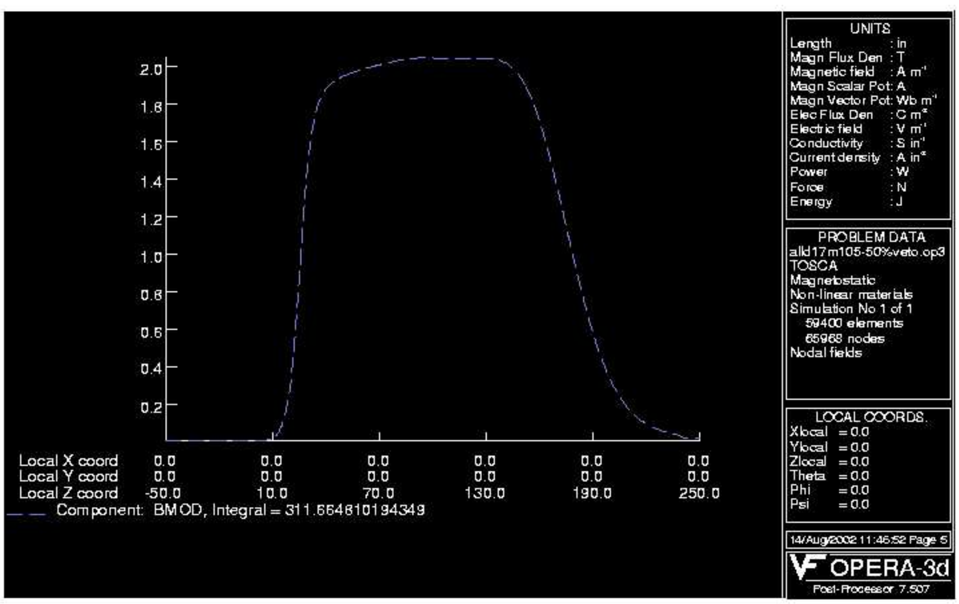


Figure 5.3 c) No upstream plug, nominal current in coils 2-4 (14000 A/in^2), but current in coils 2-4 increased by 10% (15400 A/in^2). d) No upstream plug, nominal current, and upstream iron-scintillator veto with a 50% packing fraction.

charging and discharging. The small biasing DC power supply that floats across cryostat # 1 permits a local current increase and is adjustable. This method if selected requires that a low amperage (≈300 A) current lead be added to the new cryo-reservoir during the solenoid refurbishment. The new DC biasing supply is simply connected between one of the main current leads and the low current biasing current lead. This is an adjustable, low cost, and reliable method to boost the field back up and is identical in principal to the method used to boost the down stream field. Instead of adding turns, which is difficult, one just adds some extra current to the existing turns. The magnet control and quench protection stems are marginally more complex as a result of this solution. Precautions must be taken to guarantee that there can never be a current path through the biasing lead and power supply that conducts the main 1800 A solenoid current. Figure 5.3c is a graph of the central field with extra current in the 7 coils of cryostat #1.

Upstream veto with iron radiator

The new upstream hole in the yoke provides the opportunity to use a veto calorimeter to reject events with a backward (in the lab) particle. This veto calorimeter, if made from an iron and scintillator sandwich, could significantly replace some of the missing iron. Figure 5.3d shows the central solenoid field assuming a 50% packing factor for the iron-scintillator sandwich in the upstream veto detector. The result is that most of the missing field is restored. This method has the benefit of being passive and providing a useful enhancement to the detector package. There is an extra benefit of keeping the external fields lower near the upstream end of the solenoid. The GlueX collaboration has decided to simply live with the change in the upstream field distribution caused by the large upstream diameter hole. The option to bias the current of the coils in cryostat number one will remain open until the design of the new cryo-interface module containing the solenoid current leads is completed at approximately the end of 2005.

5.10 Solenoid refurbishment activities

5.10.1 Detailed tests of the four coils

The detailed examination of the solenoids four coils began in May 2003. The goal of this detailed testing was to accurately determine the leak rates, verify

Coil	N2 shield 10^{-5}torr-liter/s	He Vessel 10^{-5}torr-liter/s	External	Pressure
1	5	ok	12in bellows	ok
2	ok	0.2	12in bellows	ok
3	4	ok	12in bellows	ok
4	0.4	ok	12in bellows	ok

Table 5.3: Status of leak and pressure testing. To date, coils one and two have been tested and have no leaks. The status of "ok" indicates a leak rate of less than10^{-9}torr-liter/s

pressure ratings and verify operation of all internal instrumentation. The Solenoid has had a 30 year history of large internal leaks which complicated operations and raised the cryogenic heat load. The internal instrumentation was known to have deteriorated and accurate checks of coil electrical properties needed to be confirmed.

Coil	Resistance Across coil (Ω)	Resistance LH Lead-Ground (Ω)	Resistance RH Lead-Ground (Ω)	Inductance (mH)
1	4.9	2.2	6.4	372
2	3.2	open	open	244
3	2.7	2.6	0.2	172
4	5.2	open	open	763

Table 5.4: Measured electrical properties of the four coils.

One of the goals of this effort was to carefully perform calibrated leak rate measurements of the four coils helium spaces, nitrogen spaces and vacuum spaces. This was necessary to quantify the leaks to guide the decision to repair. From the start this effort was complicated by the complete lack of internal sealing flanges and the eventual complete failure of all four large 18 inch vacuum closure bellows. The solenoid as originally designed relied on all welded internal joints between coils. This necessitated a cut and re-weld assembly and dis-assembly sequence. Besides being messy and electrically dangerous for cryostable coils this process does not lend it self to repeated resealing as is necessary during leak detection and correction. A decision was reached early on when good leak detection sensitivity could not be achieved to install 8 conflats on each of the four coils. This resulted in achieving leak detection sensitivity of 1×10^{-9} torr-liter per second. At this sensitivity the leaks were quickly identified and quantified. The complication due to 18 inch bellows failure was corrected by replacing the bellows. The 18 inch bellows of all four coils failed due to corrosion through the thin convolutions. Temporary solder repairs proved to be one time useful thus necessitating complete replacement. Coil four, which was not part of the MEGA experiment at LANL had a non-standard vacuum pump-out flange that required replacing. The coil electrical properties and internal instrumentation were measured during this time also. The instrumentation operability was confirmed and the wiring was verified and documented. The results of the testing is summarized in Tables 5.3, 5.4 and 5.5. The work at IUCF to test the four coils in detail and to perform such repairs as to permit the testing was concluded in February 2004. At the conclusion of this work all four coils had been extensively tested, and the leak position had been determined in coils one and two.

Coil	Voltage Taps	Carbon Resistance Thermometer (4 to 300K)	Thermocouple (80 to 300K)	Platinum Resistance (40 to 300K)	Strain Gauge (new)
1	ok	7 of 8 ok	removed	30 new	6 new
2	ok	ok	removed	30 new	6 new
3	ok	ok	TBD	TBD	TBD
4	ok	4 of 7 ok	TBD	TBD	TBD

Table 5.5: Table of internal instrumentation and voltage taps. Each coil has voltage taps (VT) and Carbon Resistance Thermometers (CRT) in the Helium vessel and Thermocouples (TC) on the N2 shield and strain gauges (SG) on the support posts.

5.10.2 Refurbishment of Coils one and two

Following the conclusion of the initial investigations, a contract was negotiated with IUCF to perform all repairs and proof testing on coils one and two. The scope of work of this effort was to localize and repair all leaks, replace all strain gauges as most had failed, replace the thermal couples shield thermometers with Platinum resistance thermometers (PT100), replace all wiring and replace the aluminized mylar multi layer insulation(MLI). A decision was made to retain the original Liquid Nitrogen shields for several reasons. Coil two was found to have no shield leaks,the leak shield leak in coil one was in the supply tube and finally the effort and cost required to replace the shields was not competitive with repair. Analysis showed that the shields had adequate flow rates for reliable thermal siphon operation. Coil two was repaired first as it had a Helium leak thus necessitating an extensive disassembly of the shield to locate. The leak was found in a weld preparation near a weld seam after removal of 1/6 of the total LN2 shield on coil 2.The leak was repaired and proof tested both for vacuum and pressure. A side benefit of finding and fixing this helium leak was finding and correcting a major piping error in the shield LN2 plumbing. It was found that two thirds of the coil two shield was in fact "dead headed". By this we mean that both supply and return for 4 of 6 shield panels were connected together and thus had no cooling flow. This must be a significant contributer to the overall historic poor shield performance. The larger effort on coil two was reconstructing the shield around the coil helium case. This was the reverse of the original assembly process which had all wet sections of the coil shields assembled first and tested and only then was the coil case inserted. This original process allows access to all sides of shield connection welds and permits easy welding or brazing and testing. The new PT100 thermometers were installed in small copper blocks soldered to the copper shield panels for good thermal contact and reliable mounting. The new strain gauges were installed on the outermost of the three nested cylinders of the cold to warm supports. The original were installed on the now inaccessible innermost cylinder. Since these strain gauges measure displacement the choice of which cylinder to mount them on can be made for convenience alone.

Coil one was previously determined to have a shield leak only. This leak was located in the supply nitrogen tube underneath the bottom of the coil. The leak was located about 18 inches from the point of connection to the shield so the tube when cut free could be bent out from under the coil and repaired. This leak was found near a soldered mounting tab.The tube section was cut out and the leak was corrected. The instrumentation of coil one was upgraded exactly the same as coil two. The most difficult part of completing coils one and two was reconnecting the shields and plumbing due to the out of sequence reassembly. This necessitated replacing the simple joints with more complex junctions that had only forward facing welds. This technique was used extensively on a magnet in JLAB 's Hall C namely the HMS Dipole. All went well until the final leak and pressure tests. Coil two was found to have a small leak with a two hour rise time and coil one although initially fond leak tight in vacuum testing sprung a new leak during pressure testing at only 30 psi (out of 100). These new leaks necessitated a new leak hunt and repair and adding a set of cold leak tests to both coils. The new leak in coil one was found near the first leak and the source was confirmed as corrosion of the stainless tube, probably due to 30 year brazing flux. Both coils were cooled to approximately 120 Kelvin using LN2 on three occasions each with Helium Mass Spec. leak tests performed just before cool down , while cold and right after warm-up. No leaks were found and the slow rate of rise "leak" in coil two did not rematerialize leading to the conclusion that the signal was not a true leak but was environmental in nature. A side benefit of this testing was the confirmation of proper operation of the new shield pt100 thermometers and the wiring correctness. both coils were pressure tested to 10o psi successfully. This concluded the testing and internal repair phase of coils one and two. The next step was to replace all the shield MLI insulation and perform a final evacuation as preparation for placing the coils in storage. Both coils one and two achieved vacuum in the range of 1×10^{-5} , passed a final leak check and were subsequently backfilled with N2 gas, sealed and moved to an inside storage location at IUCF.

5.10.3 Plans to complete coils three and four

As of the writing of this version of the design report (Sept, 2004) coils three and four have been moved into the working area at IUCF and contract negotiations for their refurbishment are underway. The scope of work for coils three and four is similar to coils one and two. Namely the location and repair of the known LN2 shield leaks in coils three and four, replacement of thermocouples with PT100's , replacement of strain gauges, replacement of sensor wiring and replacement of all MLI on the LN2 shields. This work is expected to begin in the fall of 2004 and be complete before summer 2005.

5.10.4 Plans to complete the solenoid at JLAB

The remaining work to upgrade and re-assemble and test the solenoid is planned to occur at JLAB. Activities during 2005 include securing a test and assembly space in the Test Lab at JLAB, moving coils one and two to the space in the test lab and preparing the coils for cool-down to 4.5 Kelvin. This testing effort requires equipping and staffing the solenoid test area in the test lab and designing and fabricating a new single coil test interface. The original SLAC-designed test interface was never found so a replacement is required to support testing. The replacement will have connections matching JLAB standards. A set of temporary cryogenic connection lines for use in the Test Lab will also need to be designed and fabricated. These two design and fabricate items will become the highest priority of the JLAB Hall D design and engineering staff in FY 2005. This is to support the cool-down and test of one single coil by the end of FY 2005. This test would consist of cool down and fill at 4.5 Kelvin with helium, LN2 shield cool down and fill and only limited low current operation of the coil. The Solenoid also requires an entirely new control system. The original solenoid had only manual controls and instrument data were recorded in paper log books. The cryogenic control of the solenoid was completely absent and all cooling was achieved by manipulating a small Helium refrigerator. The replacement of the controls on the HMS SC magnets at JLAB at this time and the similarity of many systems and identical nature of others is a very happy coincidence. The prototype for the solenoid new controls is being tested as this is written. A full system of the prototype is planned for January and February 2005. Following debugging and commissioning of the HMS Dipole prototype system a clone will be prepared for the Hall D solenoid. The current plan calls for a more complete test of coil two using the new solenoid controls, new power supply (already on site) and would operate a single coil at full current. Test and re-assembly of the entire solenoid are pending and depend significantly on the year of availability of Hall D.

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